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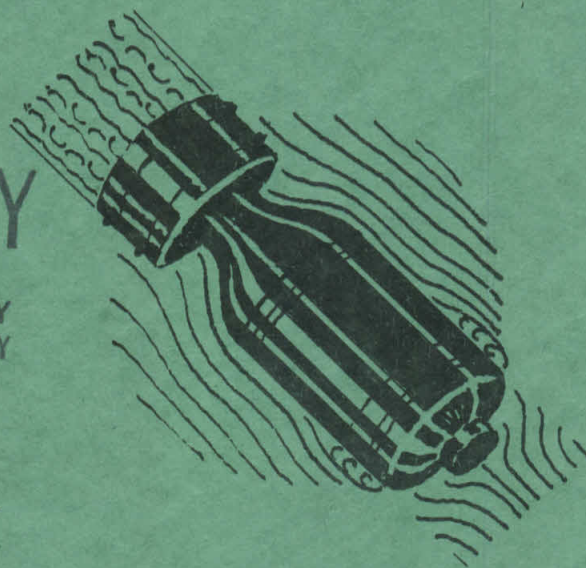
OFFICE OF SCIENTIFIC RESEARCH & DEVELOPMENT  
NATIONAL DEFENSE RESEARCH COMMITTEE  
DIVISION SIX-SECTION 6.1

# 3.5" ROTATING ROCKET WITH VARIOUS AFTERBODIES

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THE HIGH SPEED WATER TUNNEL  
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PASADENA, CALIFORNIA

SECTION NO 6.1-SR 207-1903  
HML NO ND-27.1

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OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT  
NATIONAL DEFENSE RESEARCH COMMITTEE  
DIVISION SIX -- SECTION 6.1

3.5" ROTATING ROCKET TESTS  
WITH  
VARIOUS AFTERBODIES

BY  
ROBERT T. KNAPP  
OFFICIAL INVESTIGATOR

THE HIGH SPEED WATER TUNNEL  
AT THE  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
HYDRAULIC MACHINERY LABORATORY  
PASADENA, CALIFORNIA

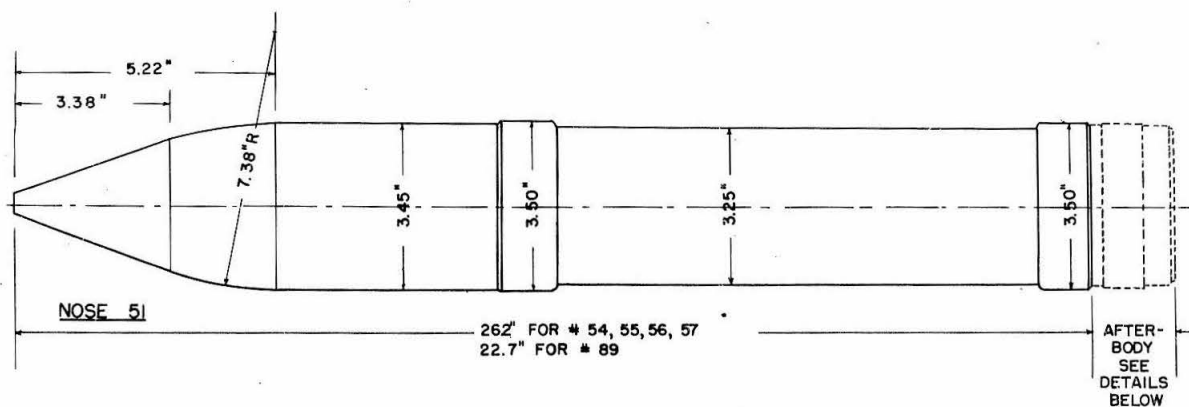
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Report Prepared by  
H. L. Doolittle  
Hydraulic Engineer

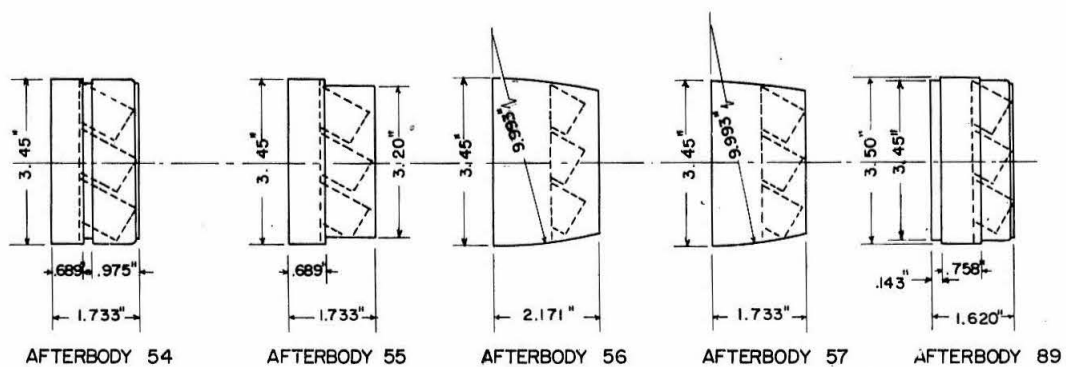
January 4, 1945

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DETAIL OF ROCKET



DETAILS OF AFTERBODIES

DETAILS OF ROCKET  
AND AFTERBODIES

FIGURE 1

### 3.5" ROTATING ROCKET TESTS WITH VARIOUS AFTERBODIES

#### GENERAL

This report is a supplement to Report Section No. 6.1-sr207-1270, dated April 21, 1944, and covers tests conducted at the High Speed Water Tunnel at the California Institute of Technology. This work was authorized by a letter of January 31, 1944, from Dr. E. H. Colpitts, Chief of Section 6.1, National Defense Research Committee, New York City.

The purpose of these tests was to determine the effect, on performance, of several different types of afterbodies. The first tests of this rocket showed that there was a slight stabilizing moment at very small yaw angles. This stabilizing moment had an undesirable effect on performance, and it was hoped that minor changes in the afterbody might overcome this difficulty.

The Appendix gives definitions of the terms used in this report, as well as a brief discussion of the required conditions for stability in a nonrotating projectile. This report deals only with static stability of a projectile without rotation.

#### DESCRIPTION OF PROJECTILE

Figure 1 is an outline drawing of the rocket corresponding to the model that was tested. This shows the rocket with a nose having the laboratory designation No. 51, which is not the nose finally adopted for this rocket as the design was changed after the tests were started. Since the change was not great, new tests were not considered necessary. It is believed that this variation will not affect the results of this investigation.

The following physical data apply to this projectile:

Length overall with Afterbodies 54, 55, 57, -	27.93"
Length overall with Afterbody 56	- 28.37"
Length overall with Afterbody 89	- 24.32"
Maximum diameter	- 3.5"
Nose to center of gravity	- 11 0"
Mass (without propellant)	- 21.75 lbs
Velocity	- 760 ft/sec
Rotation	- 181 rps

As shown in Figure 1, five different designs of afterbody were tested. These have the laboratory designation No. 54, 55, 56, 57, and 89. Design No. 89 is based on Model 23 of this projectile and the other designs are based on Model 21, the Model 23 being about 3-1/2" shorter than the others.



DESCRIPTION OF AFTERBODIES

Afterbody No. 54 is the original design adopted for the Model 24 of this projectile, the others being modifications of this.

Afterbody No. 55 is identical with No. 54 with the omission of the contact ring at the extremity of the afterbody.

Afterbody No. 56 is, in general, like No. 54 with the contact ring omitted and the end extended in a boat tail shape about 0.44" beyond the original length. This length is such that the end of the afterbody does not extend into the blast from the nozzles. In order to accomplish this, the diameter of the nozzle circle had to be reduced.

Afterbody No. 57 is similar to No. 56 except that there is no increase over the standard length and there is no change in the position of the nozzles.

Afterbody No. 89 is similar to the original except that the contact ring has been omitted and the afterbody and body proper have been shortened a total of 3.61". As before stated, this represents Model 23 of this projectile.

OPERATING CHARACTERISTICS

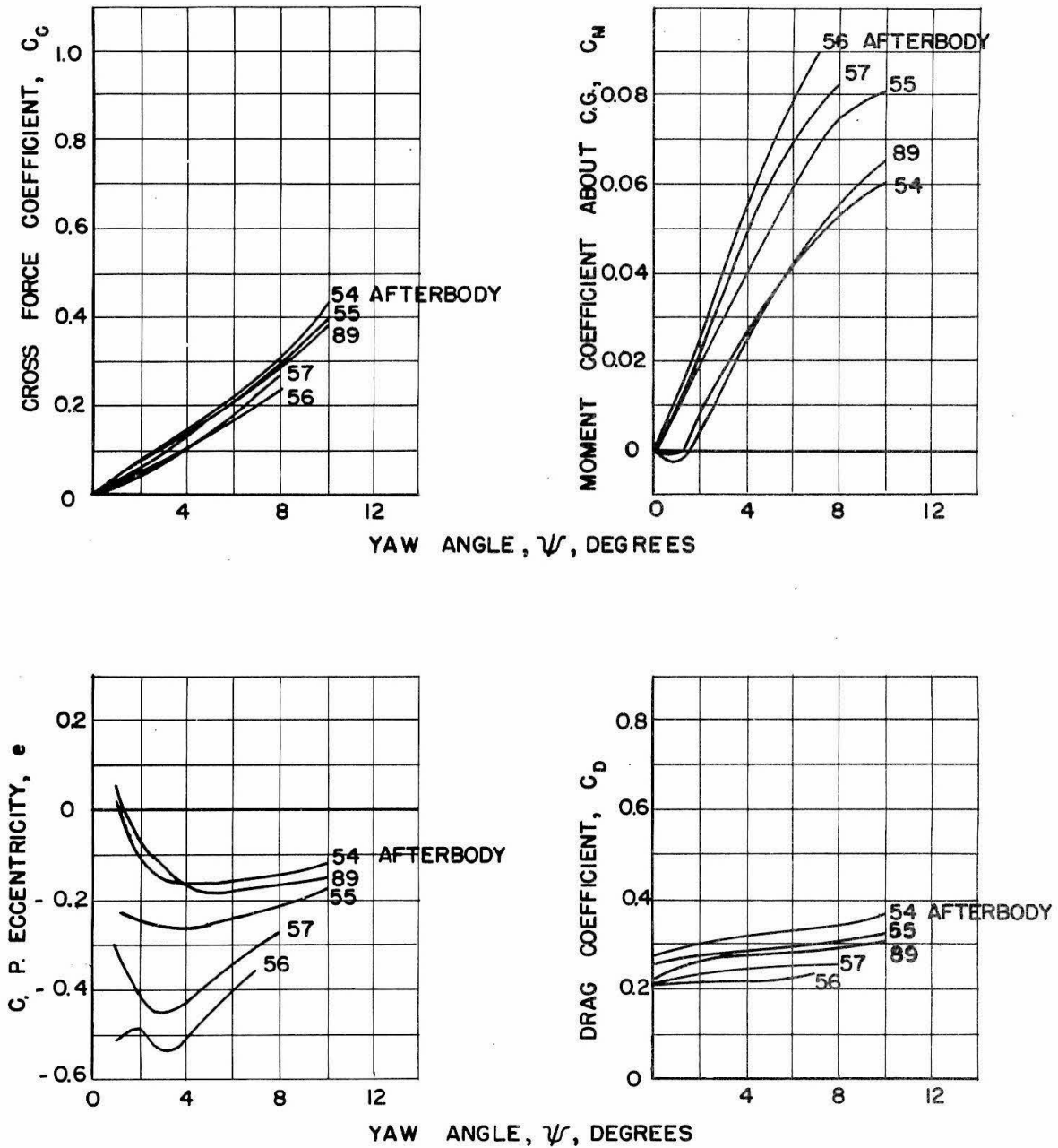
The drag, cross force, and moment coefficients, and also the C.P. eccentricity for the rocket with various afterbodies are shown in Figure 2.

It is instructive to note the decided change in drag resulting from slight changes in the shape of the afterbody. The standard blunt end afterbody (No. 54), has a drag coefficient of 0.27 at zero yaw, while Afterbodies Nos. 55, 56, and 57 all have a drag coefficient of practically 0.21 or 22% less. This would indicate that some increase in range, due to decrease in drag, could be expected by reducing the disturbance caused by the blunt afterbody.

In order to make a more easy comparison of the moment coefficients for the various afterbodies, these have been plotted to a larger scale in Figure 4. Here it is clearly seen that there is a small stabilizing moment with Afterbody No. 54 for yaws between  $0^{\circ}$  and  $1^{\circ}$ . A somewhat greater stabilizing moment results from reducing the overall length as represented by Afterbody No. 89.

The three streamlined Afterbodies Nos. 55, 56, and 57 eliminate the stabilizing moment at small yaws, which is a desirable condition for this spin stabilized projectile.

In the previous report on this projectile (Section No. 6.1-sr207-1270), curves were included showing the moment coefficient for various types of noses. These curves have been replotted to a large scale for small yaw angles and appear in this report as



ALL CURVES CORRECTED FOR  
SUPPORT INTERFERENCE.

DRAG, CROSS FORCE AND MOMENT  
COEFFICIENTS AND C. P. ECCENTRICITY

NOSE # 51 AND VARIOUS AFTERBODIES

FIGURE 2

Figure 5. It is seen that the stabilizing moment in the region from  $0^\circ$  to  $+1^\circ$  yaw is eliminated with only two of the noses tested, viz., the 7 and 14 caliber ogives. Figure 3 gives the details of these noses.

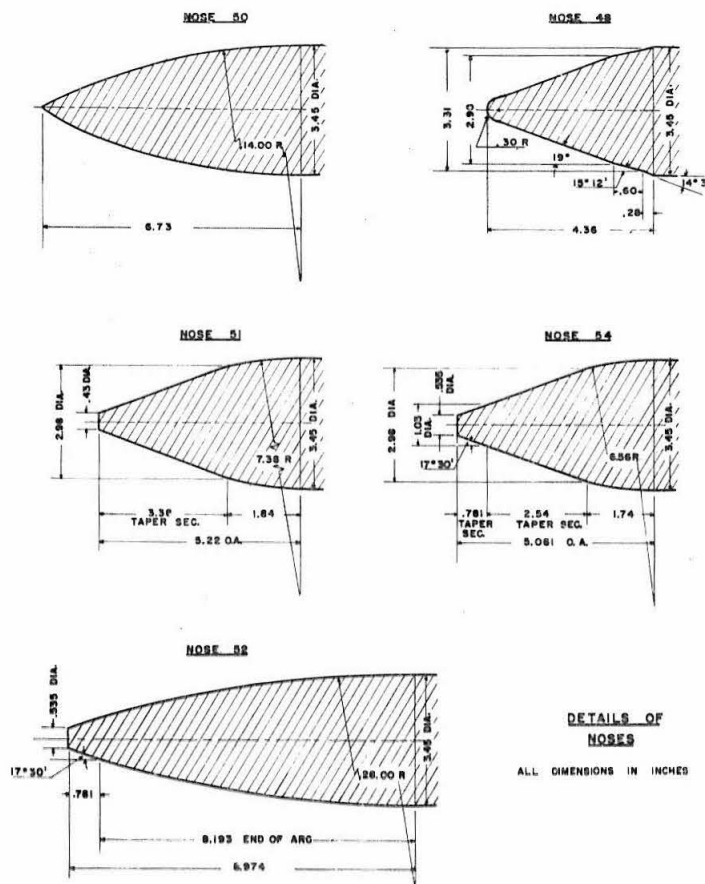
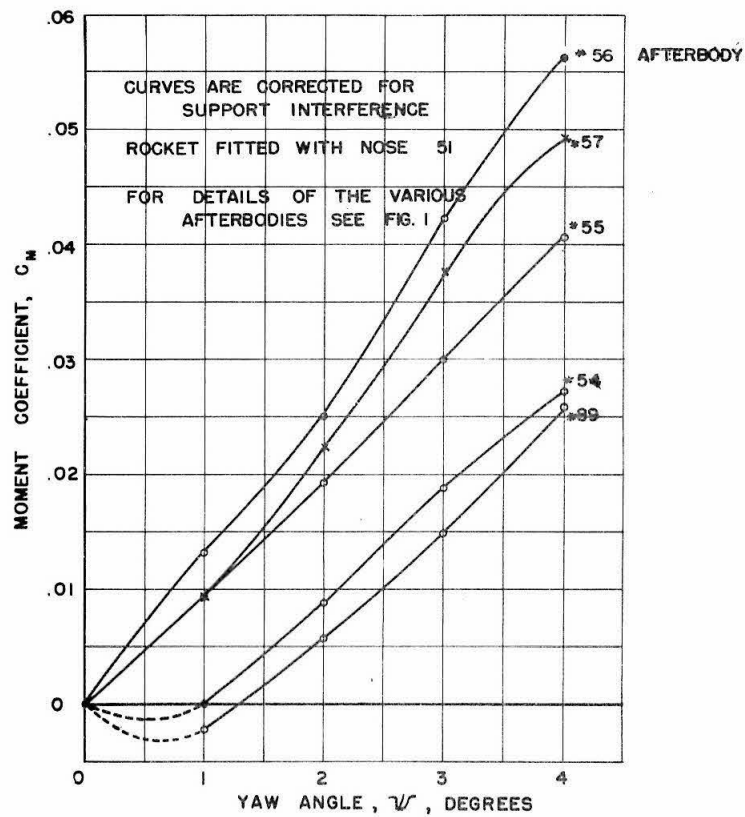


FIGURE 3

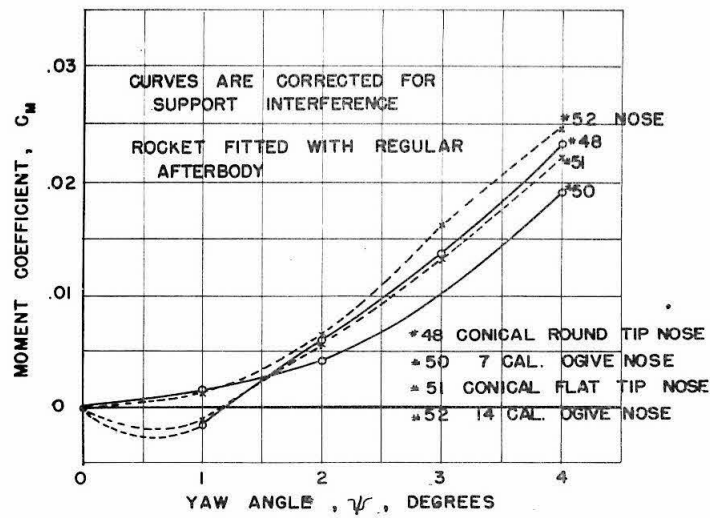
Comparing Figures 4 and 5, the relative effects produced by changes in the nose and afterbody are apparent. It is seen that, for yaws of one or two degrees, the streamlined afterbodies produce destabilizing moments more than twice as great as those obtained with the ogive noses.

In Figure 4 is shown the moment coefficient for the projectile fitted with the No. 51 nose and No. 54 afterbody, the value being 0.027 at  $4^\circ$  yaw. In Figure 5 is shown a similar curve for the No. 51 nose and No. 30 afterbody, this value for the moment coefficient being 0.022 at  $4^\circ$  yaw. The two afterbodies are identical with one exception: Afterbody No. 54 is fitted with nozzles, while No. 30 has a recessed end without nozzles. The slight difference in the ends of the afterbodies cannot account for the difference in the two values of the moment coefficient noted above. Although the discrepancy in the results of these two tests cannot be explained at this time, it is thought the tests are of value in showing relative performance.



MOMENT COEFFICIENTS FOR  
VARIOUS AFTERBODIES

FIGURE 4



MOMENT COEFFICIENTS FOR  
VARIOUS NOSES

FIGURE 5



CONCLUSIONS

This investigation indicates that the stabilizing moment at small yaw angles can be eliminated by adopting some form of boat tail shape for the afterbody similar to Nos. 55, 56, or 57 shown in Figure 1. This would also produce a destabilizing moment that, for all practical purposes, varies directly with the yaw angle.

It is realized that this streamlining of the afterbody will require a redesign of the contact ring, but it is believed the beneficial results that can be obtained justify a further study of this problem.

## APPENDIX

## DEFINITIONS

YAW ANGLE,  $\psi$ 

The angle, in a horizontal plane, which the axis of the projectile makes with the direction of motion. Looking down on the projectile, yaw angles in a clockwise direction are positive (+) and in a counterclockwise direction, negative (-).

PITCH ANGLE,  $\alpha$ 

The angle, in a vertical plane, which the axis of the projectile makes with the direction of motion. Pitch angles are positive (+) when the nose is up and negative (-) when the nose is down.

LIFT, L

The force, in pounds, exerted on the projectile normal to the direction of motion and in a vertical plane. The lift is positive (+) when acting upward and negative (-) when acting downward.

CROSS FORCE, C

The force, in pounds, exerted on the projectile normal to the direction of motion and in a horizontal plane. The cross force is positive when acting in the same direction as the displacement of the projectile nose for a positive yaw angle, i.e., to an observer facing in the direction of travel, a positive cross force acts to the right.

DRAG, D

The force, in pounds, exerted on the projectile parallel with the direction of motion. The drag is positive when acting in a direction opposite to the direction of motion.

MOMENT, M

The torque, in foot pounds, tending to rotate the projectile about a transverse axis. Yawing moments tending to rotate the projectile in a clockwise direction (when looking down on the projectile) are positive (+), and those tending to cause counterclockwise rotation are negative (-). Pitching moments tending to rotate the projectile in a clockwise direction (when looking at the projectile from the port side) are positive (+), and those tending to cause counterclockwise rotation are negative (-).

In accordance with this sign convention a moment has a de-stabilizing effect when it has the same sign as the yaw angle or the opposite sign of the pitch angle.

In all model tests the moment is measured about the point of support. Moments about the center of gravity of the projectile have the symbol,  $M_{cg}$ .

NORMAL COMPONENT, N

The sum of the components of the drag and cross force acting normal to the axis of the projectile. The value of the normal component is given by the following:

$$N = D \sin \psi + C \cos \psi \quad (1)$$

in which

N = Normal component in lbs

D = Drag in lbs

C = Cross force in lbs

$\psi$  = Yaw angle in degrees

CENTER OF PRESSURE, CP

The point in the axis of the projectile at which the resultant of all forces acting on the projectile is applied.

CENTER-OF-PRESSURE ECCENTRICITY, e

The distance between the center of pressure (CP) and the center of gravity (CG) expressed as a decimal fraction of the length (l) of the projectile. The center-of-pressure eccentricity is derived as follows:

$$e = (l_{cp} - l_{cg}) \frac{1}{l} = \frac{1}{l} \frac{M_{cg}}{N} \quad (2)$$

in which

e = Center-of-pressure eccentricity

l = Length of projectile in feet

$l_{cg}$  = Distance from nose of projectile to CG in feet

$l_{cp}$  = Distance from nose of projectile to CP, in feet

COEFFICIENTS

The three force and moment coefficients used are derived as follows:

$$\text{Drag coefficient, } C_D = \frac{D}{\rho \frac{V^2}{2} A_D} \quad (3)$$

$$\text{Cross force coefficient, } C_C = \frac{C}{\rho \frac{V^2}{2} A_D} \quad (4)$$

$$\text{Moment coefficient, } C_M = \frac{M}{\rho \frac{V^2}{2} A_D l} \quad (5)$$

in which

D = Measured drag force in lbs

C = Measured cross force in lbs

$\rho$  = Density of the fluid in slugs/cu ft =  $w/g$

w = Specific weight of the fluid in lbs/cu ft

g = Acceleration of gravity in  $\text{ft/sec}^2$

$A_D$  = Area in sq ft at the maximum cross section of the projectile taken normal to the geometric axis of the projectile

V = Mean relative velocity between the water and the projectile in ft/sec

M = Moment, in foot-pounds, measured about any particular point on the geometric axis of the projectile

l = Overall length of the projectile in feet

CONTROL ANGLE

In considering the effect of rudders on static stability, either in yaw or pitch, the term "control angle" is used to denote the yaw below which a given rudder setting with opposite sign to the yaw will tend to return the projectile to zero yaw, and above which the yaw will further increase. The control angle is useful for indicating the effectiveness of rudders and for comparing the static stability of different projectiles with equal rudder settings.

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### RUDDER EFFECT

The total increase or decrease in moment coefficient, at a given yaw or pitch angle, resulting from a given rudder setting. This increase or decrease in moment coefficient is measured from the moment coefficient curve for neutral rudder setting.

### REYNOLDS NUMBER

In comparing hydraulic systems involving only friction and inertia forces, a factor called Reynolds number is of great utility. This is defined as follows:

$$R = \frac{lV}{\nu} = \frac{lV\rho}{\mu} \quad (6)$$

in which

R = Reynolds number

l = Overall length of projectile, feet

V = Velocity of projectile, feet per sec

$\nu$  = Kinematic viscosity of the fluid, sq ft per sec =  $\mu/\rho$

$\rho$  = Mass density of the fluid in slugs per cu ft

$\mu$  = Absolute viscosity in pound-seconds per sq ft

Two geometrically similar systems are also dynamically similar when they have the same value of Reynolds number. For the same fluid in both cases, a model with small linear dimensions must be used with correspondingly large velocities. It is also possible to compare two cases with widely differing fluids provided l and V are properly chosen to give the same value of R.

### CAVITATION PARAMETER

In the analysis of cavitation phenomena, the cavitation parameter has been found very useful. This is defined as follows:

$$K = \frac{P_L - P_B}{\rho \frac{V^2}{2}} \quad (7)$$

in which

K = Cavitation parameter

$P_L$  = Absolute pressure in the undisturbed liquid, lbs/sq ft

$P_B$  = Vapor pressure corresponding to the water temperature, lbs/sq ft

V = Velocity of the projectile, ft/sec

$\rho$  = mass density of the fluid in slugs per cu ft =  $w/g$

$w$  = weight of the fluid in lbs per cu ft

$g$  = acceleration of gravity

Note that any homogeneous set of units can be used in the computation of this parameter. Thus, it is often convenient to express this parameter in terms of the head, i.e.,

$$K = \frac{h_L - h_B}{\frac{V^2}{2g}} \quad (8)$$

where

$h_L$  = Submergence plus the barometric head, ft of water

$h_B$  = Pressure in the bubble, ft of water

It will be seen that the numerator of both expressions is simply the net pressure acting to collapse the cavity or bubble. The denominator is the velocity pressure. Since the entire variation in pressure around the moving body is a result of the velocity, it may be considered that the velocity head is a measure of the pressure available to open up a cavitation void. From this point of view, the cavitation parameter is simply the ratio of the pressure available to collapse the bubble to the pressure available to open it. If the  $K$  for incipient cavitation is considered, it can be interpreted to mean the maximum reduction in pressure on the surface of the body measured in terms of the velocity head. Thus, if a body starts to cavitate at the cavitation parameter of one, it means that the lowest pressure at any point on the body is one velocity head below that of the undisturbed fluid.

The shape and size of the cavitation bubbles for a specific projectile are functions of the cavitation parameter. If  $p_B$  is taken to represent the gas pressure within the bubble instead of the vapor pressure of the water, as in normal investigations, the value of  $K$  obtained by the above formula will be applicable to an air bubble. In other words, the behavior of the bubble will be the same whether the bubble is due to cavitation, the injection of exhaust gas, or the entrainment of air at the time of launching.

The following chart gives values of the cavitation parameter as a function of velocity and submergence in sea water.

#### GENERAL DISCUSSION OF STATIC STABILITY

Water tunnel tests are made under steady flow conditions, consequently the results only indicate the tendency of the steady state hydrodynamic couples and forces to cause the projectile to return to or move away from its equilibrium position after a



disturbance. Dynamic couples and forces including either positive or negative damping are not obtained. If the hydrodynamic moments are restoring the projectile, then it is said to be statically stable, if nonrestoring, statically unstable. In the discussion of static stability the actual motion following a perturbation is not considered at all. In fact, the projectile may oscillate continuously about an equilibrium position without remaining in it. In this case it would be statically stable, but would have zero damping and hence, be dynamically unstable. With negative damping a projectile would oscillate with continually increasing amplitude following an initial perturbation even though it were statically stable. Equilibrium is obtained if the sum of the hydrodynamic, buoyant, and propulsive moments equal zero. In general, propulsive thrusts act through the center of gravity of the projectile so only the first two items are important.

If a projectile is rotating from its equilibrium position so as to increase its yaw angle positively, the moment coefficient must increase negatively (according to the sign convention adopted) in order that it be statically stable. Therefore, for projectiles without controls or with fixed control surfaces, a negative slope of the curve of moment coefficient vs yaw gives static stability and a positive slope gives instability. For a projectile without controls, static stability is necessary for a successful flight unless stability is obtained by spinning as in the case of rifle shells. For a projectile with controls, stabilizing moments can be obtained by adjusting the control surfaces, and the slope of the moment coefficient, as obtained with fixed rudder position, need not give static stability. Where buoyancy either acts at the center of gravity or can be neglected, equilibrium is obtained when the hydrodynamic moment coefficient equals zero. For symmetrical projectiles this occurs at zero yaw angle, i.e., when the projectile axis is parallel to the trajectory. For nonsymmetrical projectiles, such as a torpedo when the rudders are not neutral, the moment is not zero at zero yaw but vanishes at some definite angle of attack. Where buoyancy cannot be neglected equilibrium is obtained when  $C_M = -C_{Buoyancy}$  and the axis of the projectile is at some angle with the trajectory.

For symmetrical projectiles the degree of stability or instability can be obtained from the center-of-pressure curves. If the center of pressure falls behind the center of gravity, a restoring moment exists giving static stability. If the center of pressure falls ahead of the center of gravity, the moment is nonrestoring, and the projectile will be statically unstable. The degree of stability or instability is indicated approximately by the distance between the center of gravity and the center of pressure. In general, for nonsymmetrical projectiles, the cross force or lift is not zero when the moment vanishes so that the center of pressure curve is not symmetrical and the simple rules just stated cannot be used to determine whether or not the projectile will be stable. In such cases careful interpretation of the moment curves is a more satisfactory method of determining stability relationship.

